SOLAR/2014-79/14

Solar Energy System Performance Evaluation

BLAKEDALE PROFESSIONAL CENTER
OFFICE UNIT
Greenwood, South Carolina
October, 1978 through March, 1979

U.S. Department of Energy

National Solar Heating and
Cooling Demonstration Program

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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

BLAKEDALE PROFESSIONAL CENTER
OFFICE SUITE
GREENWOOD, SOUTH CAROLINA

OCTOBER 1978 THROUGH MARCH 1979

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TABLE OF CONTENTS

SECTION	TITLE	PAGE
1.	FOREWORD	1
2.	SUMMARY AND CONCLUSIONS	3
3.	SYSTEM DESCRIPTION	7
4.	PERFORMANCE EVALUATION TECHNIQUES	11
5.	PERFORMANCE ASSESSMENT	13
	5.1 Weather Conditions	14
	5.2 System Thermal Performance	16
	5.3 Subsystem Performance	19
	5.3.1 Collector Array Subsystem	20
	5.3.2 Storage Subsystem	28
	5.3.3 Hot Water Subsystem	32
	5.3.4 Space Heating Subsystem	33
	5.4 Operating Energy	36
	5.5 Energy Savings	38
6.	REFERENCES	41
APPENDIX A	DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS	A-1
APPENDIX B	SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE BLAKEDALE PROFESSIONAL CENTER	B-1
APPENDIX C	LONG-TERM AVERAGE WEATHER CONDITIONS	C-1

LIST OF FIGURES AND TABLES

FIGURE	TITLE	PAGE
3-1	Blakedale Professional Center Solar Energy System Schematic	8
5.3.1-1	Collector Array Operating Point Histogram and Instantaneous Efficiency Curves	26

TABLE	TITLE	PAGE
5.1-1	Weather Conditions	15
5.2-1	System Thermal Performance	17
5.2-2	Solar Energy System Coefficients of Performance	18
5.3.1-1	Collector Array Performance	21
5.3.1-2	Energy Gain Comparison	24
5.3.2-1	Storage Subsystem Performance	30
5.3.4-1	Heating Subsystem Performance	34
5.4-1	Operating Energy	37
5.5-1	Energy Savings	39

NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Blakedale Professional Center project site is designated as SOLAR/2014-79/14. The elements of this designation are explained in the following illustration:

SOLAR/2014-79/14

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Year — 79

Report Type Designation — 14

- Demonstration Site Number:

  Each Project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

  - Solar Energy System Performance Evaluations are designated by the number 14.

  - Solar Project Descriptions are designated by the number 50.

  - Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate, and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter

presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the Blakedale Professional Center solar energy system are listed in Section 6, References.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Blakedale Professional Center solar energy system. The analysis covers operation of the system from October 1978 through March 1979. A detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgements are extended to those individuals involved in the operation of the Blakedale Professional Center solar energy system. Their insight and cooperation in the resolution of various on-site problems during the reporting period were invaluable.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation Report provides an operational summary of the solar energy system installed at the Blakedale Professional Center Office Suite in Greenwood, South Carolina. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

The measurement data were collected (References [7 - 12])* by the National Solar Data Network(NSDN) [1] for the period October 1978 through March 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

Features of this report include: a system description, a review of actual system performance during the report period, analysis of performance based on evaluation of meteorological load and operational conditions, and an overall discussion of results.

Monthly values of average daily insolation and average outdoor ambient temperature measured at the Blakedale Professional Center site are presented in Table 5.1-1. Also presented in the table are the long-term, average monthly values for these climatic parameters.

The energy collection and storage subsystem commenced operation on October 16, 1978 for the current heating season. By mid December, collector

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*Numbers in brackets designate References found in Section 6.

circulating pump P1 frequently failed to start automatically when solar energy was available at the collectors, although it always stopped automatically. For this reason, the resident contractor monitored the operation of this pump and manually started it after the control system had failed. This semi-automatic operation continued until April 19, 1979, at which time the heating season terminated. This control system failure resulted in less than optimal energy collection through the heating season.

Even when pump P1 started automatically, it was frequently premature, resulting in unintentional energy rejection by the collector array. The pump also continued to run after there was no energy gain by the collectors. As a result, solar energy was transferred from thermal storage to the collectors and subsequently dissipated to the environment for short periods of time. This loss was accelerated whenever the pump cycled frequently, as during periods of low level and intermittent insolation.

The collector array subsystem was not operational from March 25 through March 29, 1979. Cumulative evaporation losses from the open storage system reduced the amount of water in thermal storage to a level that prevented pump P1 from circulating the water to the collectors.

The domestic hot water subsystem was operational over the entire six month period except for one week. On February 20, 1979, a leak developed in the pipe between heat exchanger HX1 and flow rate sensor W300. As a result, approximately 0.73 million Btu of solar energy were lost to the environment before this leak was discovered and subsequently repaired.

The space heating subsystem commenced operation on October 18, 1978 for the current heating season. However, the subsystem was not operational from December 27, 1978 through January 1, 1979 and from March 25 through March 29, 1979. In both cases, cumulative evaporation losses from the system reduced the amount of water in thermal storage to a level that prevented pump P2 from circulating the water that delivers solar energy to heat exchanger HX2.

Prior to mid January, pump P2 started whenever there was a demand for heating, even when there was no available solar energy in thermal storage. For this reason, the resident contractor modified the control system whereby he manually operated this pump as appropriate. By March, this procedure was modified so that the pump ran continuously. This semi-automatic operation permitted the control system to transfer solar energy from storage to either heat exchanger HX2 or around this heat exchanger as governed by the position of the motorized valve. This mode of operation resulted in an increased operating energy expenditure and increased energy transport losses.

During the six month period from October 1978 through March 1979, 14 percent (12.39 million Btu) of the 86.54 million Btu system load was provided by solar energy, resulting in a net electrical energy savings of 4.69 million Btu.

During the reporting period, the measured average outside ambient temperature was 53°F, or two degrees higher than the long-term average of 51°F. As a result, a total of 2,296 heating degree-days were accumulated as opposed to the long-term expected total of 2,727. The measured average daily insolation in the plane of the collector array was 1,267 Btu/ft^2, which was seven percent below the long-term daily average of 1,357 Btu/ft^2. Both long-term values are computed from averages derived from the weather station in Greenville, South Carolina.

A total of 220.45 million Btu of solar energy were incident upon the collector array during the reporting period. When the collector array was operating, a total of 124.27 million Btu was incident on the array. The subsystem collected 33.29 million Btu, which represents an operational collector efficiency of 27 percent.

A total of 30.69 million Btu of solar energy was delivered to storage, and 14.31 million Btu were removed from storage. From this, 12.39 million Btu were delivered to the space heating load. The difference represents transport losses. The average effective storage heat loss coefficient was 102 Btu/Hr-°F. The variations among the individual monthly values used to

compute the effective storage heat transfer coefficient, and hence, the variations in the coefficient itself are attributable to the unusual operating circumstances.

There was essentially no requirement for water from the domestic hot water subsystem during the reporting period. Therefore, no performance data for this subsystem has been included in this report.

The space heating load was 86.54 million Btu for the reporting period. Solar energy provided 12.39 million Btu of this total, and the remaining 74.15 million Btu were supplied by the heat pump and electrical resistance heater. This resulted in a heating solar fraction of 14 percent, and a net savings of 4.69 million Btu of electrical energy.

In general, the Blakedale Professional Center solar energy system performance was not up to expectations during this six-month period. System problems of significance were the intermittent operation of both the energy collection and storage subsystem and the space heating subsystem, and modifications to the associated control system, which resulted in excessive and inefficient operation of the collection and solar space heating subsystems.

3. SYSTEM DESCRIPTION

The Blakedale Professional Center solar energy system is designed to provide 85 percent of the space heating requirements and 100 percent of the domestic hot water heating requirements for a 4,400 square foot office suite in Greenwood, South Carolina. Solar energy is collected by 53 flat-plate collectors, which are manufactured by PPG Industries. The collectors, having a gross area of 954 square feet, are mounted on the roof in three banks. Each collector array faces south at an angle of 45 degrees from the horizontal. The heat transfer medium is 99 percent water and one percent corrosion inhibitor. Solar energy is stored in a 5,000-gallon tank buried under the parking lot. The tank is insulated with four inches of sprayed-on polyurethane covered with a waterproof coating. When solar energy is inadequate, auxiliary space heating is provided by a 10-ton heat pump and a 36-kilowatt electric resistance heater. Auxiliary hot water is provided by a 40-gallon electric heater. Freeze protection is provided by a drain-down system.

The system, shown schematically in Figure 3-1, has four modes of operation:

Mode 1 - Collector-to-Storage: This mode is entered when the difference between the temperature of the collector and the temperature of water near the bottom of the water thermal storage is greater than 19°F. Pump P1 circulates water through the collectors to transfer solar energy to the water thermal storage. This mode terminates when the temperature differential is less than 6°F, or the temperature of water in the collector is less than 37°F.

Mode 2 - Storage-to-Office Area (Solar): This mode is entered when heat is required in the office area. Pump P2 circulates water through the water thermal storage to heat exchanger HX2 in the air-handling unit. This mode terminates when the supply air temperature is greater than 120°F, or the requirement for heat is satisfied.

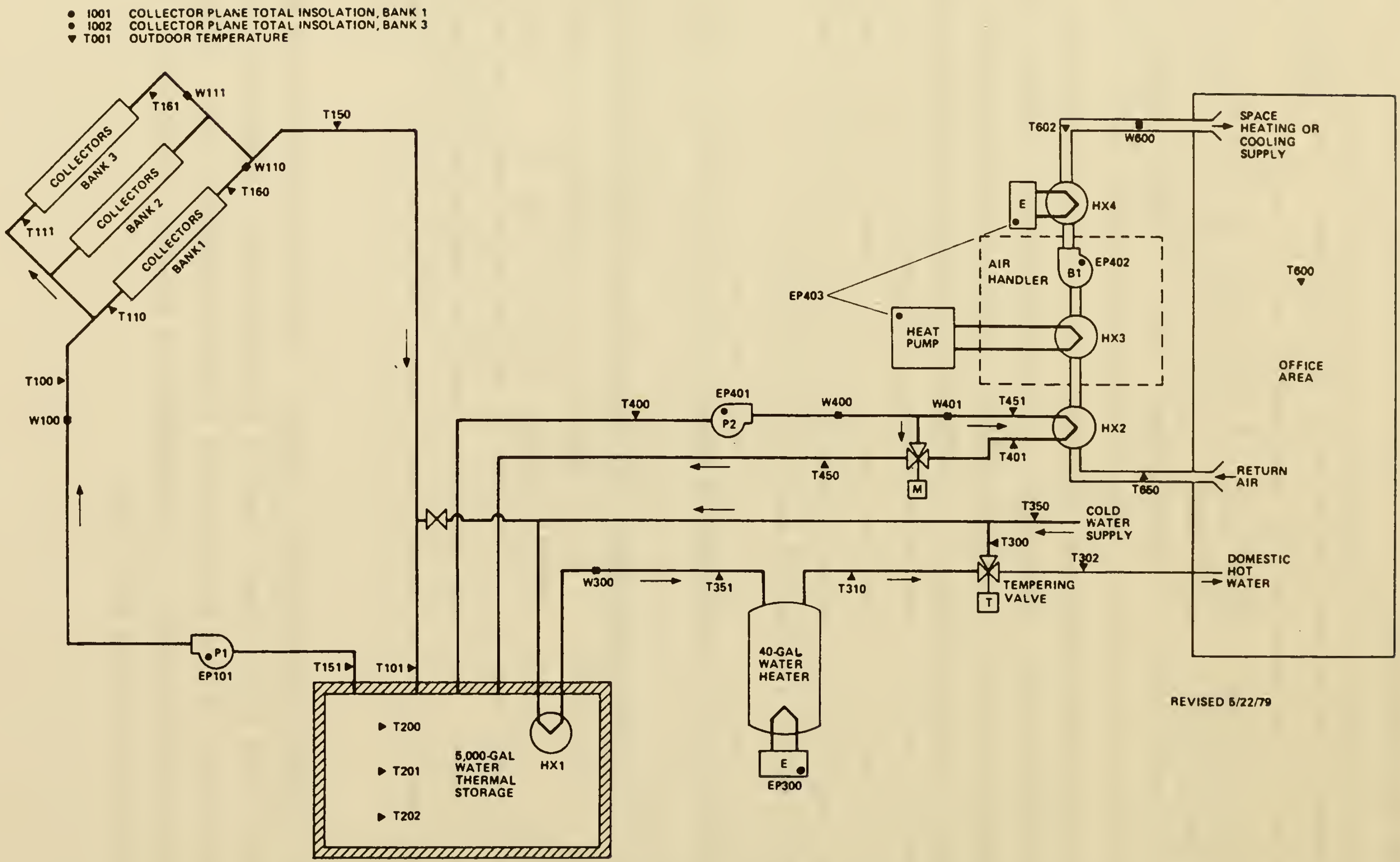

FIGURE 3-1 BLAKEDALE PROFESSIONAL CENTER SOLAR ENERGY SYSTEM SCHEMATIC

Mode 3 - Storage-to-Office Area (Auxiliary): Although this mode is not a solar mode of operation, it is entered concurrently with Mode 2 when heat is required in the office and the office return air temperature is less than 65°F. A 10-ton heat pump is energized to provide heat to heat exchanger HX3. When the outside air temperature is less than 40°F, two 18-kilowatt electric resistance heaters are energized in stages to provide auxiliary energy to heat exchanger HX4. This mode terminates when the office return air temperature is greater than 68°F, or the requirement for heat is satisfied.

Mode 4 - Domestic Hot Water Heating: This mode is entered when there is a requirement for hot water. As hot water is drawn, cold water passes through heat exchanger HX1 in the water thermal storage, and subsequently through the water heater and tempering valve to provide 120°F. This mode terminates when the requirement for hot water is satisfied.

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Blakedale Professional Center solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Blakedale Professional Center site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, October 1978 through March 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

[illegible]

[illegible]

[illegible]

5. PERFORMANCE ASSESSMENT

The performance of the Blakedale Professional Center solar energy system has been evaluated for the October 1978 through March 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the details relating to the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the domestic hot water subsystem and the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

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* f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

5.1 Weather Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the Blakedale Professional Center site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are asccumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree-days are summed monthly.

During the period from October 1978 through March 1979, the temperature in Greenwood, South Carolina was higher than normal as evidenced by a measured average outside ambient temperature of 53°F when compared to the long-term value of 51°F. In addition, the cloud cover was greater than normal, as evidenced by the measured average daily insolation in the plane of the collector array of 1,267 Btu/ft^2, as compared to the long-term daily average value of 1,357 Btu/ft^2. As a result, the requirement for space heating was smaller than normal, as was the amount of solar energy available for collection over this six-month period. Both long-term values are computed from averages derived from the weather station at Greenville, South Carolina.

TABLE 5.1-1

WEATHER CONDITIONS

	Daily Incident Solar Energy Per Unit Area (45° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree-Days		Cooling Degree-Days	
Month	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Oct 78	1,716	1,565	65	63	56	125	73	59
Nov 78	1,016	1,395	60	52	155	384	7	2
Dec 78	1,015	1,142	48	45	514	634	1	0
Jan 79	1,192	1,160	41	44	748	655	0	3
Feb 79	1,158	1,356	43	46	611	528	0	4
Mar 79	1,503	1,523	59	53	212	401	25	18
Total	--	--	--	--	2,296	2,727	106	86
Average	1,267	1,357	53	51	383	455	18	14

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined to be the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution.

The thermal performance of the Blakedale Professional Center solar energy system is presented in Table 5.2-1 and Table 5.2-2. This performance assessment is based on the six-month period from October 1978 through March 1979.

During the period from October 1978 through March 1979, 14 percent (12.39 million Btu) of the 86.54 million Btu system load was provided by solar energy, compared to the expected system solar fraction of 67 percent (57.90 million Btu). These differences were due primarily to the control system problems and other system abnormalities that occurred during the reporting period.

The solar energy system COP (defined as the total solar energy delivered to the load divided by the total solar energy system operating energy) was 3.68 for the six-month period. The collector array subsystem COP and the space heating subsystem solar COP for the six-month period were 23.78 and 6.29, respectively. These values again relate the amount of solar energy associated with a particular subsystem to the amount of electrical energy required to operate the solar portion of that subsystem. As such, the COP serves as an indicator of both how well the system was designed and how well it operated. At the Blakedale Professional Center site the solar energy supplied to the total load is the same as the solar energy supplied to the space heating load, and this is the reason that the overall system COP appears low with respect to the space heating COP.

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Oct 78	5.03	3.27	3.30	0.52	100	18
Nov 78	5.22	5.78	5.70	4.01	99	72
Dec 78	3.73	14.66	10.10	1.57	69	11
Jan 79	5.77	28.14	14.30	2.33	51	8
Feb 79	3.90	24.92	14.70	0.77	59	3
Mar 79	9.64	9.77	9.80	3.19	100	33
Total	33.29	86.54	57.90	12.39	---	--
Average	5.55	14.42	9.65	2.07	67	14

TABLE 5.2-2

SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP
Oct 78	2.08	27.94	7.43
Nov 78	9.55	20.88	23.59
Dec 78	3.14	20.72	4.91
Jan 79	3.38	25.09	5.07
Feb 79	2.48	18.57	7.70
Mar 79	2.66	27.54	3.75
Total Period	3.68	23.78	6.29

5.3 Subsystem Performance

The Blakedale Professional Center solar energy installation may be divided into four subsystems:

1) Collector array
2) Storage
3) Domestic hot water
4) Space heating.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the four subsystems for the period October 1978 through March 1979.

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i \tag{1}$$

where:

η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy (SECA)

Q_i = Incident Solar Energy (SEA).

The gross collector array area is 954 square feet. The measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s/\left(Q_{oi} \times \frac{A_p}{A_a}\right) \tag{2}$$

where:

Q_s = Collected Solar Energy (SECA)

Q_{oi} = Operational Incident Energy (SEOP)

A_p = Gross Collector Area (product of the number of collectors and the total envelope area of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware (GCAA).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Oct 78	50.74	5.03	0.10	17.76	0.28
Nov 78	29.07	5.22	0.18	23.38	0.22
Dec 78	30.03	3.73	0.12	14.57	0.26
Jan 79	35.25	5.77	0.16	22.16	0.26
Feb 79	30.92	3.90	0.13	15.93	0.24
Mar 79	44.44	9.64	0.22	30.47	0.32
Total	220.45	33.29	--	124.27	--
Average	36.74	5.55	0.15	20.71	0.27

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Collector Array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5.3.1-1.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

The Blakedale Professional Center collector array consists of 53 flat-plate collectors that are arranged into three banks on the roof. The lowest bank contains 23 panels whereas each of the other banks contains 15 panels. Each bank faces south at an angle of 45 degrees from the horizontal. The heat transfer medium is 99 percent water and one percent of corrosion inhibitor. The Collector-to-Storage Mode (Mode 1) is entered when the temperature of the collector is 19°F greater than the temperature of water in thermal storage. This mode is terminated when the temperature difference is less than 6°F, or the temperature of the collector is less than 37°F.

The energy collection and storage subsystem was operational from October 16, 1978 through March 24, 1979 and after March 29, 1979. Due to a control malfunction pump P1 did not always start automatically after mid December. The operational efficiency ranged from 22 percent in November to 32 percent in March, and averaged 27 percent. A total of 33.29 million Btu was collected out of a total of 124.27 million Btu that were incident on the collector array when it was operating. Table 5.3.1-2 presents a comparison of the actual performance of the collector array for the month of March. March was chosen as the example month because the measured insolation was approximately equal to the long-term average and the collector array was operational during most of the month.

Instantaneous efficiency curves are derived from laboratory test data supplied by the collector manufacturer and from empirical sources. The three empirically derived curves are: a linear regression line fit through field data obtained in March; a linear regression line fit through all field data in the base; and a curvilinear (second order) regression line fit through all field data in the base (the base data consists of all measurments relating to collector array performance made from October 1978 through March 1979).

Each error value presented in the error field of Table 5.3.1-2 is computed by the equation

$$\text{error} = (A - P) / P \qquad (3)$$

where:

A is the actual energy gain of the collector array shown in column one (million Btu/day)

P is the predicted energy gain of the collector array based on projecting the measured operating point to the applicable instantaneous efficiency curve and multiplying by the measured insolation level and collector array area and then summing over all the measured operating points (million Btu/day).

TABLE 5.3.1-2

ENERGY GAIN COMPARISON
MARCH

SITE: BLAKEDALE GREENWOOD, SC

		ERROR			
		FIELD DERIVED			LAB
DAY	ACTUAL	MONTH	LONG TERM	2ND ORDER	PANEL
1	2.046E+05	-0.175	-0.132	-0.126	-0.571
2	5.311E+05	-0.076	-0.016	-0.002	-0.495
3	7.401E+02	-3.552	0.597	-1.211	-0.869
4	0.000E+00	0.000	0.000	0.000	0.000
5	5.024E+05	0.050	0.105	0.119	-0.454
6	4.379E+05	-0.089	-0.044	-0.041	-0.532
7	5.034E+05	0.160	0.221	0.229	-0.397
8	3.080E+05	0.087	0.104	0.211	-0.508
9	5.671E+05	0.133	0.185	0.195	-0.426
10	7.323E+04	-0.331	-0.349	-0.236	-0.740
11	2.779E+05	0.009	0.038	0.060	-0.519
12	5.810E+05	-0.005	0.044	0.048	-0.490
13	4.802E+05	0.084	0.123	0.137	-0.471
14	2.716E+05	-0.092	-0.058	-0.035	-0.554
15	4.788E+05	-0.028	0.013	0.024	-0.514
16	3.640E+05	0.285	0.303	0.366	-0.423
17	5.761E+05	0.246	0.284	0.313	-0.404
18	4.391E+05	-0.062	-0.033	-0.011	-0.550
19	4.801E+05	0.107	0.142	0.175	-0.470
20	3.840E+05	-0.039	-0.003	0.021	-0.529
21	2.130E+05	0.095	0.118	0.194	-0.495
22	2.491E+04	-0.184	-0.343	3.941	-0.813
23	0.000E+00	0.000	0.000	0.000	0.000
24	3.486E+04	1.581	1.598	2.321	0.131
25	0.000E+00	0.000	0.000	0.000	0.000
26	0.000E+00	0.000	0.000	0.000	0.000
27	0.000E+00	0.000	0.000	0.000	0.000
28	0.000E+00	0.000	0.000	0.000	0.000
29	0.000E+00	0.000	0.000	0.000	0.000
30	4.973E+05	-0.016	0.032	0.073	-0.453
31	1.838E+05	-0.335	-0.312	-0.289	-0.677
	8.393E+06	0.018	0.058	0.087	-0.496

CURVE	COEFFICIENTS			
	A0 (FRTA)	A1 (FRUL)	A2 (*)	R**2
PANEL	0.720	-0.870	N.A.	N.A.
MONTH	0.433	-0.912	N.A.	0.254
LT1ST	0.398	-0.761	N.A.	0.331
LT2ND	0.371	-0.299	-1.686	N.A.

The computed error is then a measure of how well the particular prediction curve fits the reality of dynamic operating conditions in the field. The data presented in Table 5.3.3-2 indicates a strong disparity between performance predictions based on single panel laboratory tests and actual results obtained from field operation of this array of panels.

The slight difference shown for solar energy collected during March in Table 5.3.1-1 and Table 5.3.1-2 is primarily due to the abnormal operation of pump P1 and the fact that no rejected energy is included in the computations used to generate the data presented in Table 5.3.1-2.

Figure 5.3.1-1 presents a histogram of the collector array operating points for March. Also presented in Figure 5.3.1-1 are linear instantaneous efficiency curves based on controlled laboratory test data supplied by the collector manufacturer, field data for the month of March and long-term field data for the base period. The ordinate of the graph shown in Figure 5.3.1-1 has a printed range of 0 to 10 percent to display the distribution of collector array operating points. However, the value printed on the ordinate should be multiplied by 10 when the intercepts of the linear instantaneous efficiency curves are being evaluated (these values range from 0 to 100 percent).

The collector array operating points, X, are calculated each scan by the equation

$$X = (T_{f,i} - T_a) / I \qquad (4)$$

where:

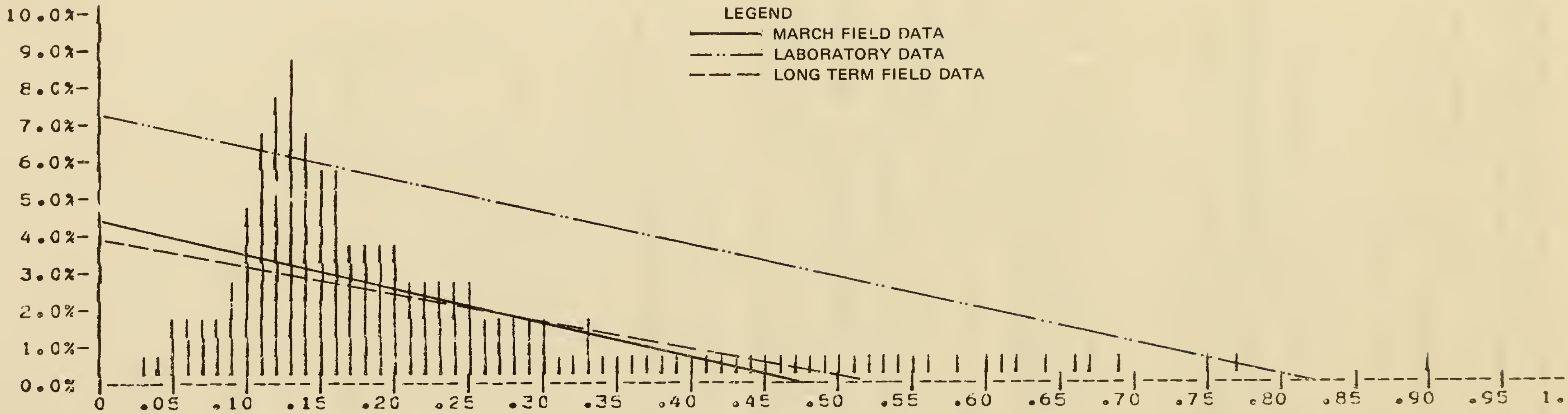
$T_{f,i}$ is the inlet temperature of the collector array transport fluid (°F)

T_a is the temperature of the ambient air (°F)

I is the insolation rate (Btu/ft^2-hr).

BLAKEDALE GREENWOOD, SC

COLLECTOR TYPE: PFC COLLECTOR MODEL: A414



OPERATING POINT HISTOGRAM – MARCH

FLUID PROPERTIES – MARCH

	WATER			
	COEFFICIENTS			
PROPERTY	A0	A1	A2	A3
SPECIFIC HEAT	1.011E+00	-2.348E-04	1.037E-06	
DENSITY	8.346E+00	4.129E-04	-9.961E-06	

ARRAY FLOW RATE 16.75 GPM

PANEL FLOW RATE 0.32 GPM

AVERAGE TEMPERATURE GAIN 7.58 DEGR FAHRENHEIT

LONG TERM CURVE FIT VALID FROM 0.027 TO 0.242 .

FIGURE 5.3.1-1. COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES

Examination of the operating point histogram indicates that the predominant region of collector array operation occurred for operating points between 0.10 to 0.20 (64 percent of the time). This leads to the expectation that the operational collector array efficiency would typically be on the order of 0.30, which is approximately 11 percent above the value of 0.27 presented in Table 5.3.1-1.

The long-term first order curve shown in Figure 5.3.1-1 has a slightly less negative slope than the curve derived from single panel laboratory test data. This is attributable to lower losses resulting from array effects. The laboratory predicted instantaneous efficiency is not in close agreement with the curves derived from actual field operation. This indicates that the laboratory derived curves might not be useful for design purposes in an array configuration of this type.

It is suspected that the irregular operation of pump P1 may have contributed to the relatively poor collector performance noted in this analysis.

Additional information concerning collector array analysis in general may be found in a forthcoming paper [13] that describes collector array analysis procedures in detail and presents the results of analysis performed on numerous collector array installations across the United States.

5.3.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \qquad (5)$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH)

Q_{so} = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium (STEO)

Q_{si} = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI).

Evaluation of the system storage performance under actual transient system operation and weather conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the storage subsystem design can be derived empirically as a function of storage average temperature (average storage temperature for the reporting period) and the ambient temperature in the vicinity of the storage tank.

An effective storage heat transfer coefficient (C) for the storage subsystem can be defined as follows:

$$C = (Q_{si} - Q_{so} - \Delta Q_s)/[(\bar{T}_s - \bar{T}_a) \times t] \frac{\text{Btu}}{\text{Hr-°F}} \qquad (6)$$

where:

C = effective storage heat transfer coefficient

Q_{si} = energy to storage (STEI)

Q_{so} = energy from storage (STEO)

ΔQ_s = change in stored energy (STECH)

$\bar{T}_s$ = storage average temperature (TS)

$\bar{T}_a$ = average ambient temperature in the vicinity of storage (TE)

t = number of hours in the month (HM).

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in the report period and included, along with Stroage Average Temperature, in Table 5.3.2-1.

The Blakedale Professional Center thermal storage consists of a 5,000 gallon tank that is buried adjacent to the parking lot. The tank is insulated with four inches of polyurethane foam and a waterproof coating.

TABLE 5.3.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Storage Heat Loss Coefficient (Btu/Hr-°F)
Oct 78	4.76	0.74	1.34	0.44	105	88
Nov 78	5.12	4.28	-2.08	0.43	118	75
Dec 78	3.71	1.74	0.43	0.59	96	65
Jan 79	5.40	2.59	0.08	0.49	95	118
Feb 79	3.41	0.81	-0.49	0.10	93	159
Mar 79	8.29	4.15	0.61	0.57	108	108
Total	30.69	14.31	-0.11	--	--	--
Average	5.12	2.39	-0.02	0.46	103	102

As discussed in Section 2, the energy collection and storage subsystem was operational from October 16, 1978 through March 24, 1979 and after March 30, 1979, although pump P1 did not always start automatically after mid December. The storage efficiency ranged from 0.10 for February to 0.57 for March and averaged 0.46 for this six-month period.

In general, the energy to storage was less than would be expected due to the unintentional rejection of stored energy resulting from improper operation of pump P1 over the six-month period. Similarly, the energy extracted from storage was less than expected due to the inconsistent manual operation of pump P2 during February. Prior to mid January, the energy extracted from storage was greater than expected due to a space heating control system mode which removed energy from storage whenever there was a demand for space heating. The same situation existed in March, but was due to excessive manual operation of pump P2. The original control system design permitted the removal of solar energy from thermal storage whenever there was a demand for heating regardless of the temperature of the stored water. These factors had a corresponding impact on the effective storage heat loss coefficient.

5.3.3 Hot Water Subsystem

The performance of the hot water subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total hot water load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the hot water solar fraction. The calculated hot water solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total hot water load supported by solar energy.

The Blakedale Professional Center domestic hot water heating subsystem consists of a heat exchanger in the space heating subsystem thermal storage and a 40-gallon conventional electric water heater. The domestic hot water preheating mode (Mode 4) is entered when there is a requirement for hot water. This mode is terminated when the requirement for hot water is satisfied.

Except for one week, the domestic hot water heating subsystem was operational over the entire six-month period. However, there was essentially no requirement for hot water, as evidenced by the fact that the resident contractor did not operate the electric water heater. An insignificant amount of solar energy was removed from thermal storage whenever the hot water faucets were opened. This load is neglected, and assumed to be zero. As a result, the associated performance factors are zero.

5.3.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy. The performance of the space heating subsystem is presented in Table 5.3.4-1.

The Blakedale Professional Center space heating subsystem consists of a solar supplied heat exchanger in an existing air-handling unit, a 10-ton heat pump and a 36-kilowatt electric resistance heater. Solar energy is supplied when Storage-to-Office area mode (Mode 2) is entered. This mode is terminated when the supply air temperature is greater than 120°F, or the requirement for heat is satisfied. There is no direct collector to load solar energy mode.

The space heating subsystem was operational from October 18, 1978 through December 26, 1978; from January 2, 1979 through March 24, 1979; and after March 30, 1979. The resident contractor did not consistently monitor the requirement for space heating and implement manual control of the solar energy in storage from mid January through February. The solar fraction of the load ranged from a low of three percent in February to a maximum of 72 percent in November and averaged 14 percent. During the six-month reporting period, solar energy provided 12.39 million Btu of the 86.54 million Btu space heating subsystem load.

In general, the solar energy used was less than nominal due to the inconsistent manual operation of pump P2 during February. However, the solar energy used was larger than nominal (due to the original space heating control system design) prior to mid January and larger than nominal in March due to

TABLE 5.3.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Oct 78	3.27	0.52	2.75	1.08	18
Nov 78	5.78	4.01	1.77	0.81	72
Dec 78	14.66	1.57	13.09	7.13	11
Jan 79	28.14	2.33	25.81	12.06	8
Feb 79	24.92	0.77	24.15	10.23	3
Mar 79	9.77	3.19	6.58	2.43*	33
Total	86.54	12.39	74.15	33.74	--
Average	14.42	2.07	12.36	5.62	14

* Does not include evaporator blower.

the manual operation of pump P2. The original control system permitted the removal of solar energy from thermal storage whenever there was a demand for heating regardless of the temperature of the water in storage.

5.4 Operating Energy

Operating energy for the Blakedale Professional Center solar energy system is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 5.4-1.

At the Blakedale Professional Center, the energy collection and storage subsystem consumed 1.40 million Btu of electrical energy to operate Pump P1. This operating energy was larger than nominal due to the anomalous operation of pump P1 over this six-month period.

The domestic hot water heating subsystem does not require any operating energy and, hence, did not consume any electrical energy.

The space heating subsystem consumed 6.86 million Btu of electrical energy to operate pump P2 and blower B1 in the air-handling unit. In general, this operating energy was larger than expected due to the excessive operation of pump P2 after February, although the operation of this pump was intermittent during February.

A total of 8.26 million Btu of electrical operating energy was required to support operation of the complete system during the reporting period.

TABLE 5.4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 78	0.18	0.71	0.89
Nov 78	0.25	0.54	0.79
Dec 78	0.18	1.01	1.19
Jan 79	0.23	1.76	1.99
Feb 79	0.21	1.22	1.43
Mar 79	0.35	1.62	1.97
Total	1.40	6.86	8.26
Average	0.23	1.14	1.38

5.5 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

At the Blakedale Professional Center, the space heating subsystem contains a heat pump and an electric resistance heater to provide auxiliary thermal energy. The COP for the heat pump was considered to be equal to two for October, November, December and January. For February and March, this COP was calculated as a function of the ambient (outside) temperature. The resistance heater was considered to be 100 percent efficient for computational purposes.

Electrical energy savings for the six-month reporting period are presented in Table 5.5-1. The space heating subsystem saved a total of 6.10 million Btu of electrical energy which resulted in a net savings of 4.69 million Btu (1,375 kwh) after the operating energy for the energy collection and storage subsystem is deducted. This is equivalent to 15.62 million Btu of fossil energy at the source of power generation. In general, the electrical energy savings were somewhat low due to the reasons discussed in the previous section.

TABLE 5.5-1

ENERGY SAVINGS

Month	Electrical Energy Savings Space Heating (Million Btu)	Heat Pump COP	ECSS Operating Energy (Million Btu)	Net Savings		Fossil Equivalent At Source (Million Btu)
				Million Btu	kwh	
Oct 78	0.21	2.0	0.18	0.03	9	0.10
Nov 78	1.58	2.0	0.25	1.33	390	4.43
Dec 78	0.48	2.0	0.18	0.29	85	0.97
Jan 79	0.71	2.0	0.23	0.48	141	1.60
Feb 79	2.77	*	0.21	2.56	750	8.52
Mar 79	0.35	*	0.35	0.0	0	0.0
Total	6.10	-	1.40	4.69	1375	15.62
Average	1.02	-	0.23	0.78	229	2.60

* COP computed as a function of outdoor ambient temperature.

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7.* Monthly Performance Report, Blakedale Professional Center, SOLAR/2014-78/10, Department of Energy, Washington (October 1978).

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11.* Monthly Performance Report, Blakedale Professional Center, SOLAR/2014-79/02, Department of Energy, Washington (February 1979).

12.* Monthly Performance Report, Blakedale Professional Center, SOLAR/2014-79/03, Department of Energy, Washington (March 1979).

13. McCumber, W. H. Jr., "Collector Array Performance for Instrumented sites of the National Solar Heating and Cooling Demonstration Program," to be published and distributed at the 1979 Solar Update Conference.

* Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The energy collection and storage subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-removing aperature, including the framework, which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow to and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction, is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, the outlet hot water temperature, and the total hot water consumption.

- <u>HOT WATER LOAD</u> (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- <u>SOLAR FRACTION OF LOAD</u> (HWSFR) is the percentage of the load demand which is supported by solar energy.

- <u>SOLAR ENERGY USED</u> (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- <u>OPERATING ENERGY</u> (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- <u>AUXILIARY THERMAL USED</u> (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>AUXILIARY ELECTRICAL FUEL</u> (HWAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- SUPPLY WATER TEMPERATURE (TSW) is the average inlet temperature of the water supplied to the subsystem.

- AVERAGE HOT WATER TEMPERATURE (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- HOT WATER USED (HWCSM) is the volume of water used.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- <u>SPACE HEATING LOAD</u> (HL) is the sensible energy added to the air in the building.

- <u>SOLAR FRACTION OF LOAD</u> (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- <u>SOLAR ENERGY USED</u> (HSE) is the amount of solar energy supplied to the space heating subsystem.

- <u>OPERATING ENERGY</u> (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- <u>AUXILIARY THERMAL USED</u> (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>AUXILIARY ELECTRICAL FUEL</u> (HAE) is the amount of electrical energy supplied directly to the subsystem.

- <u>ELECTRICAL ENERGY SAVINGS</u> (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE BLAKEDALE PROFESSIONAL CENTER

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$

AVERAGE BUILDING TEMPERATURE (°F)

$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$

WHEN THE COLLECTOR LOOP IS ACTIVE

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD(T_2, T_1) = \int_{T_1}^{T_2} C_p(T)dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$SECA = \Sigma\ [M100 \times HWD\ (T150, T100)] \times \Delta\tau$

ECSS OPERATING ENERGY (BTU)

$CSOPE = 56.8833 \times \Sigma\ EP101 \times \Delta\tau$

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma\ [M100 \times HWD(T101,\ T151)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE

$$STEO = \Sigma\ [M300 \times HWD(T351,\ T350) + M400 \times HWD(T400,\ T450)] \times \Delta\tau$$

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST = (1/60) \times \Sigma\ [(T201 + T202 + T203)/3] \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWSE = \Sigma\ [M300 \times HWD(T351,\ T350)] \times \Delta\tau$$

HOT WATER LOAD (BTU)

$$HWL = \Sigma\ [M300 \times HWD(T310,\ T350)] \times \Delta\tau$$

HOT WATER AUXILIARY ELECTRIC ENERGY (BTU)

$$HWAE = 56.8833 \times \Sigma\ EP300 \times \Delta\tau$$

HOT WATER CONSUMED (GALLONS)

$$HWCSM = \Sigma\ [M300/RHO(T351)] \times \Delta\tau$$

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$$HSE = \Sigma\ [M401 \times HWD(T451,\ T401)] \times \Delta\tau$$

SPACE HEATING AUXILIARY THERMAL ENERGY (BTU)

$$HAT = 0.7 \times 56.8833 \times \Sigma\ EP403 \times \Delta\tau$$

WHEN HEAT PUMP IS OPERATING

$$HAT = 56.8833 \times \Sigma\ EP403 \times \Delta\tau$$

WHEN HEAT STRIPS ARE OPERATING

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE

SPACE HEATING LOAD (BTU)

$$HL = \Sigma [M600 \times HRF \times (T602 - T650)] \times \Delta\tau$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = 56.8833 \times \Sigma [EP401 + EP402] \times \Delta\tau$$

SPACE HEATING SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$$HAE = 56.8833 \times \Sigma EP402 \times \Delta\tau$$

COLLECTED SOLAR ENERGY (BTU/FT^2)

$$SEC = SECA/CLAREA$$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$$SEA = CLAREA \times SE$$

COLLECTOR ARRAY EFFICIENCY

$$CAREF = SECA/SEA$$

SUPPLY WATER TEMPERATURE (°F)

$$TSW = T310$$

HOT WATER TEMPERATURE (°F)

$$THW = T350$$

BOTH TSW AND THW ARE COMPUTED ONLY WHEN FLOW EXISTS IN THE SUBSYSTEM, OTHERWISE THEY ARE SET EQUAL TO THE VALUES OBTAINED DURING THE PREVIOUS FLOW PERIOD.

CHANGE IN STORED ENERGY (BTU)

$$STECH = STOCAP \times (STOTP - STOTP_p)$$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE

SOLAR ENERGY TO LOADS (BTU)

$$SEL = HWSE + HSE$$

ENERGY DELIVERED TO LOAD SUBSYSTEMS FROM ECSS (BTU)

$$CSEO = HWSE + HSE$$

STORAGE EFFICIENCY

STEFF = (STECH + STEO)/STEI

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

HOT WATER AUXILIARY THERMAL ENERGY (BTU)

HWAT = HWAE

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

WHERE HWTKSE AND HWTKAUX REPRESENT THE CURRENT SOLAR AND AUXILIARY ENERGY CONTENT OF THE HOT WATER TANK

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = HPFRAC x HL/HPCOP + (1-HPFRAC) x HL - (HAE + HOPE)

SPACE HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HSE/HL)

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HAE + HWAE

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HOPE + CSOPE

SYSTEM LOAD (BTU)

SYSL = HL + HWL

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

$$TSVE = HWSVE + HSVE - CSOPE$$

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

$$SFR = (HL \times HSFR + HWL \times HWSFR)/SYSL$$

SYSTEM PERFORMANCE FACTOR

$$SYSPF = SYSL/((AXE + SYSOPE) \times 3.33)$$

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: BLAKEDALE 13. LOCATION: GREENWOOD SC

ANALYST: J. THOMAS PDRIVE NO.: 39.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 34.20 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1635.	741.	0.45314	1.565	1160.	655	3	44.
FEB	2072.	999.	0.43220	1.357	1356.	528	4	46.
MAR	2612.	1335.	0.51105	1.141	1523.	401	18	53.
APR	3141.	1711.	0.54466	0.950	1625.	118	38	62.
MAY	3488.	1851.	0.53067	0.828	1532.	20	186	70.
JUN	3619.	1910.	0.52771	0.779	1483.	0	360	[illegible]
JUL	3546.	1818.	0.51262	0.802	1458.	0	443	[illegible]
AUG	3267.	1685.	0.51570	0.893	1505.	0	419	[illegible]
SEP	2797.	1408.	0.50347	1.056	1487.	5	243	73.
OCT	2226.	1198.	0.53825	1.306	1565.	125	59	63.
NOV	1735.	896.	0.51625	1.557	1395.	384	2	52.
DEC	1512.	693.	0.45841	1.648	1142.	634	0	45.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.